THE EFFECT OF TOOL HANDLE SIZE AND SHAPE ON GRIPPING FORCE

A THESIS

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SUMMARY

The object of this study was to investigate the relationship between the diameter and shape of hand tool handles and the muscular tension exerted by the operator in using the tool. The study was conducted for the purpose of providing a means of checking current size and shape recommendations for handles against physiological criteria and to provide a more objective basis for handle design.

In order to investigate the effects of handle shape and diameter on muscle tensions, an experiment was conducted in which a subject held handles of different shapes and diameters against a constant torque. Three handle shapes were used, a concave, cylindrical, and convex shape. Five diameters ranging from 11/16 in. to 1 7/16 in. in increments of 3/16 in. were used for each shape of handle. Special apparatus was used so that a constant torque could be applied to the handle while the subject held it.

The tension in the subject's flexor digitorum sublimis muscle was measured by electromyography. Surface electrodes were used and the tension measurements were recorded on film for analysis. The measuring equipment was that of the Warm Springs Foundation, Warm Springs, Georgia. The data were extracted from the film by projecting the muscle action potential (muscle tension) trace onto graph paper and

measuring its width relative to a standard calibration trace.

The data were analysed using the analysis of variance and multiple range test techniques. This analysis showed that there were significant differences between some shapes and diameters, and how these different shapes and diameters ranked with respect to muscle tension.

Upon examining the results of this study the following conclusions were reached, subject to the limitations of the study:

(1) Using tension in the finger flexing muscles as the criterion for comparison of the handle shapes tested, there are no real differences between the shapes in the diameter range of 7/8 in. to 1 7/16 in.

(2) There are differences between the shapes tested in the 11/16 in. diameter, such that in this diameter the convex shape is inferior and the concave shape is superior to the cylindrical shape.

(3) Handle diameter has a greater influence upon muscle tension in gripping the handle than does handle shape for the shapes and diameters tested.

(4) Dreyfuss' recommendation of 7/8 in. as the lower limit for handle diameter is substantiated with respect to finger flexing muscle tension for the cylindrical and convex shaped handles tested.

(5) For the three shapes tested the larger handles,

1 1/4 in. and 1 7/16 in. diameter, are superior in the cylindrical shape but do not make a significant difference with the other shapes.

CHAPTER I

INTRODUCTION

The object of this study is to investigate the relationship between the diameter and shape of hand tool handles and the muscular tension exerted by the operator in using the tool. The study is being conducted for the purpose of providing a means of checking current size and shape recommendations for handles against physiological criteria, and to provide a more objective basis for handle design.

For many years industrial engineers have recognized the need for matching the tool with the man. Taylor (1) conducted studies on shoveling and found that there was an optimum-sized shovel for a man to use. Later, Gilbreth (2) remarked that "the influence of tools used upon the output is large," and emphasized the importance of matching the tool with the man.

On the problem of the design of handles, Barnes (3) made a significant contribution in his Principle of Motion Economy, which he states as follows:

> Handles such as those used on cranks and large screwdrivers should be designed to permit as much of the surface of the hand to come into contact with the handle as possible. This is particularly true when considerable force is exerted when using the handle. For light assembly work the screwdriver handle should be so shaped that it is smaller at the bottom than at the top.

Unfortunately the descriptive terms " . . . as much of the surface of the hand . . . as possible" and " . . . considerable force . . ." are not operational. Furthermore, this principle is based on studies which use work output and force decrement on a hand ergometer as criteria of handle design. These criteria are not believed to be valid because of the difficulty of controlling the level of motivation of the test subject.

Researchers in the field of Human Engineering make hardly any mention of the problem at all. McCormick (4) emphasizes the size of cranks and handwheels with respect to the control of dial pointers, and Dreyfuss (5) gives a range of optimum diameters of 7/8" to 1 1/4" for hand grips, remarking further that cylindrical grips should conform to use and hand motion and that "thin handles cut under heavy loading." while "fat handles feel insecure." Woodson (6) mentions only hand rail diameter in passing, and Tufts College Institute (7) quotes Barnes directly without considering the problem further. Neither Wood (8) nor Witt (9) consider the problem in detail. Wood only gives a dimension for poles (to be grasped) and then passes on to the dimensions of other types of handles, such as ring handles, T-Bar handles, and finger handles (which are not under consideration in this study), and knobs. Witt does not discuss handle size and shape specifically, but is more concerned with a general approach to designing handles. Other writers in the human engineering field, such as Fitts (10), are concerned mainly with visual displays, knobs, pointers, and tracking problems, neglecting the problem of handle design completely.

Some isolated studies have taken up the problem of the design and choice of specific handles, handgrips, and tools. Bobbert (11) investigated the optimal form and dimensions for concrete building block handgrips, but concluded only that maximal lifting power was a better criterion for evaluating minor changes in building block dimensions than energy expenditure or heart rate. Briggs (12) studied the effect of hammer weight on nailing and concluded that nailing efficiency was related to both hammer weight and the size of the nail. Binkhorst and Carlsoo (13) made a significant finding in their study of the thumb-forefinger grip on the handles of small instruments such as dentists' drills. In this study it was concluded that as pressure increased the subject's muscle activity increased and that with a decrease in the diameter of the tool muscle activity increased.

Other studies have been made concerning the grip strength of the human hand. Chapanis (14) measured the strength of the human hand grip, and Tuttle _et al._ (15) investigated the relation of maximum grip strength to grip strength endurance. In this study it was found that the per cent of maximum grip strength that could be maintained for one minute was correlated with maximum grip strength.

Burke et al. (16) in studying the effect of age on grip strength and grip strength endurance found that there is a rapid increase in both maximum grip strength and grip strength endurance up to 25 years of age, and then a gradual decline in both until 79 years of age. (In this study the oldest subject was 79 years old, and the curve was not extrapolated beyond that age.) None of these studies considered the design of handles and grips with respect to grip strength, however.

Another facet of the problem is that of gripping method, or type of grip. (See below: "Physiological Background.") Napier (17) divides the movements of the hand into two main groups. The first group includes the prehensile (grasping) movements, in which an object is seized and held partly or wholly within the compass of the hand. The second group is that of the nonprehensile movements in which no grasping takes place, but in which objects are pushed or lifted by the hand as a whole or by the fingers individually. Landsmeer (18) bases his work on Napier's conclusions and states that, "the nature of the activity finally influences the pattern of the grip." He continues that there are four voluntary acts in gripping: 1) opening of the hand, 2) positioning of the fingers, 3) approach of the fingers to the object, and 4) transition to the actual grip. This study is, of course, concerned primarily with the last stage.

The problem of hand tool handle design with respect to physiological criteria has not been extensively studied as a problem in itself. Rather, contributions to its solution have been made by researchers in several disciplines, but the problem itself is not solved.

CHAPTER II

PHYSIOLOGICAL BACKGROUND

In order to provide a basis for investigating the influence of handle shape and diameter on muscle tension, this chapter will be devoted to a discussion of the physiology of muscular contraction and gripping.

Muscular Contraction

There are three kinds of muscles in the human body, the voluntary skeletal muscle, the involuntary smooth muscle of the intestines, and cardiac muscle (19). It is the skeletal, or striated, muscle with which we are primarily concerned, since it is this kind of muscle that responds to intellectual control to produce the force for human movement.

The fundamental unit of skeletal muscle is the muscle cell, or fiber. These fibers are contained in a tubular sheath (sarcolemma), and a whole muscle is made up of many bundles of fiber, all bound together. The whole muscle is connected to the bones by tendons.

A muscle exerts force or does mechanical work by contracting against a load. There are two types of muscular contraction which are of interest, the isotonic contraction and the isometric contraction. When a muscle contracts isotonically, its length changes but its tension remains constant, and it is this type of contraction which provides mechanical work by moving a body member (20). When a muscle contracts isometrically, no external mechanical work is done because the muscle does not change in length and, therefore, does not cause movement of a body member. This type of contraction occurs when the muscle is contracting against a static load, as when one simply holds a weight in the palm of his hand without moving it.

The Chemistry of Muscular Contraction

A contracting muscle derives its energy from a series of chemical reactions. According to Langley (21) these reactions occur in two stages, the initial stage which is rapid and independent of oxygen, and the recovery stage which is slow and requires oxygen.

A resting muscle has three main chemical constituents:

1. Adenosine Triphosphate (ATP)
2. Phosphocreatine
3. Glycogen

When a muscle contracts, adenosine triphosphate is converted to adenosine diphosphate and energy. Then the adenosine diphosphate is in turn converted to adenosine monophosphate, and more energy is released. It is this energy that is used by the muscle to contract and exert force.

The phosphocreatine changes to creatine, releasing energy, and this energy is used for the resynthesis of adenosine triphosphate from adenosine monophosphate. The phosphocreatine is in turn resynthesized from creatine by the use of energy released by the reactions whereby glycogen is transformed to lactic acid. It should be noted that in this series of reactions (the initial stage) no oxygen is required. It is for this reason that a muscle can maintain a series of contractions without an oxygen supply.

Recovery (the second stage) is accomplished by the oxidation of about one fifth of the lactic acid. The energy resulting from this oxidation is used to convert the remaining four fifths of the original lactic acid back into glycogen. Figure 1 illustrates the chemistry of muscular contraction.

Muscle Activation

The stimulus (electrical) which elicits muscular contraction is supplied by the nerve, and one nerve axon (fiber) may innervate several muscle fibers. The nerve cell body and the long axon plus its terminal branches and all the muscle fibers supplied by these branches constitute one motor unit (22). See Figure 2.

In general each fiber has its own threshold of activation, below which no excitation will occur. When the electrical nerve impulse reaches the threshold value the fiber contracts maximally, and it is therefore said to obey an all or none law (23). Although each fiber has its own threshold of response, the threshold value for each fiber

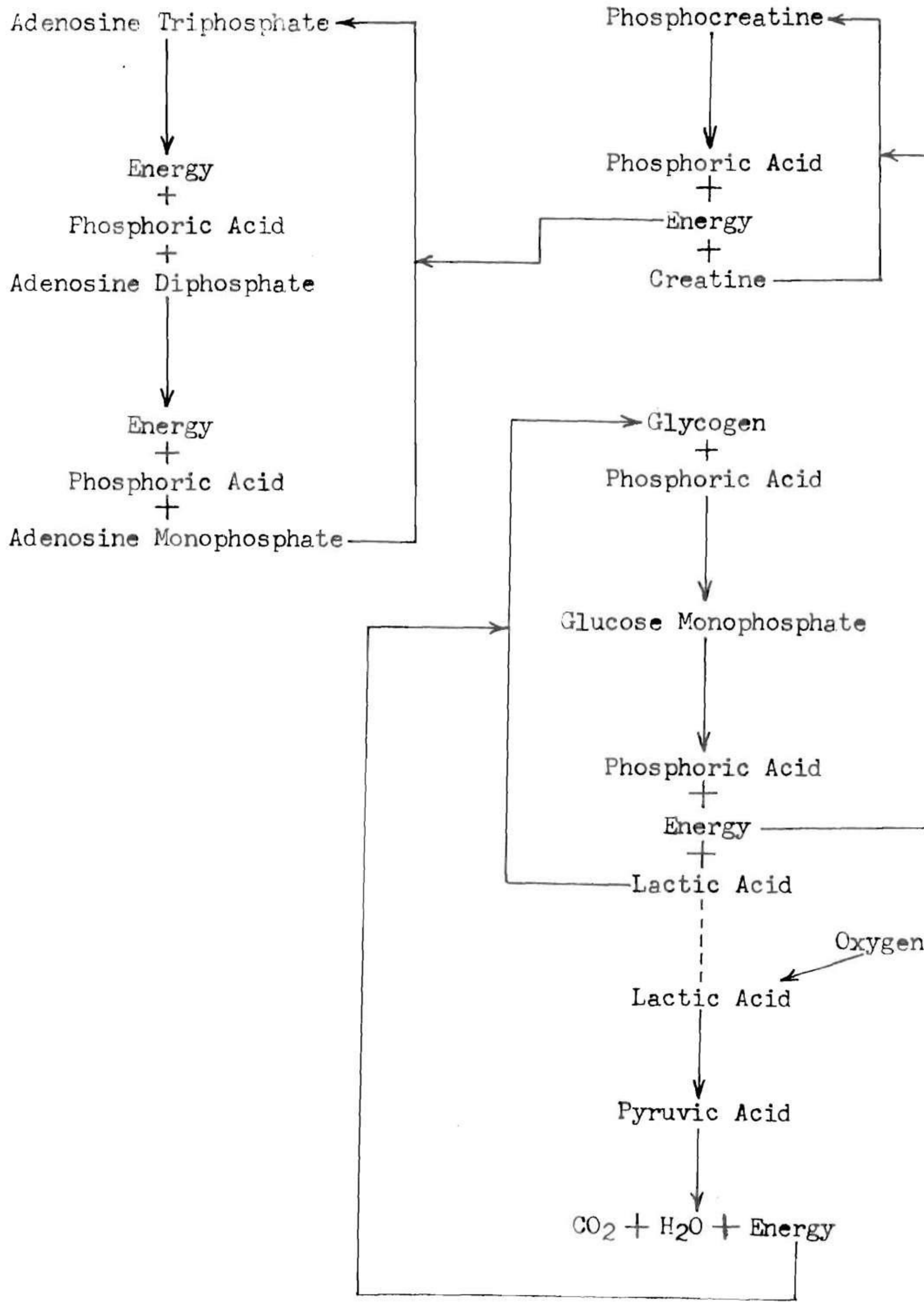


Figure 1. The Chemistry of Muscular Contraction

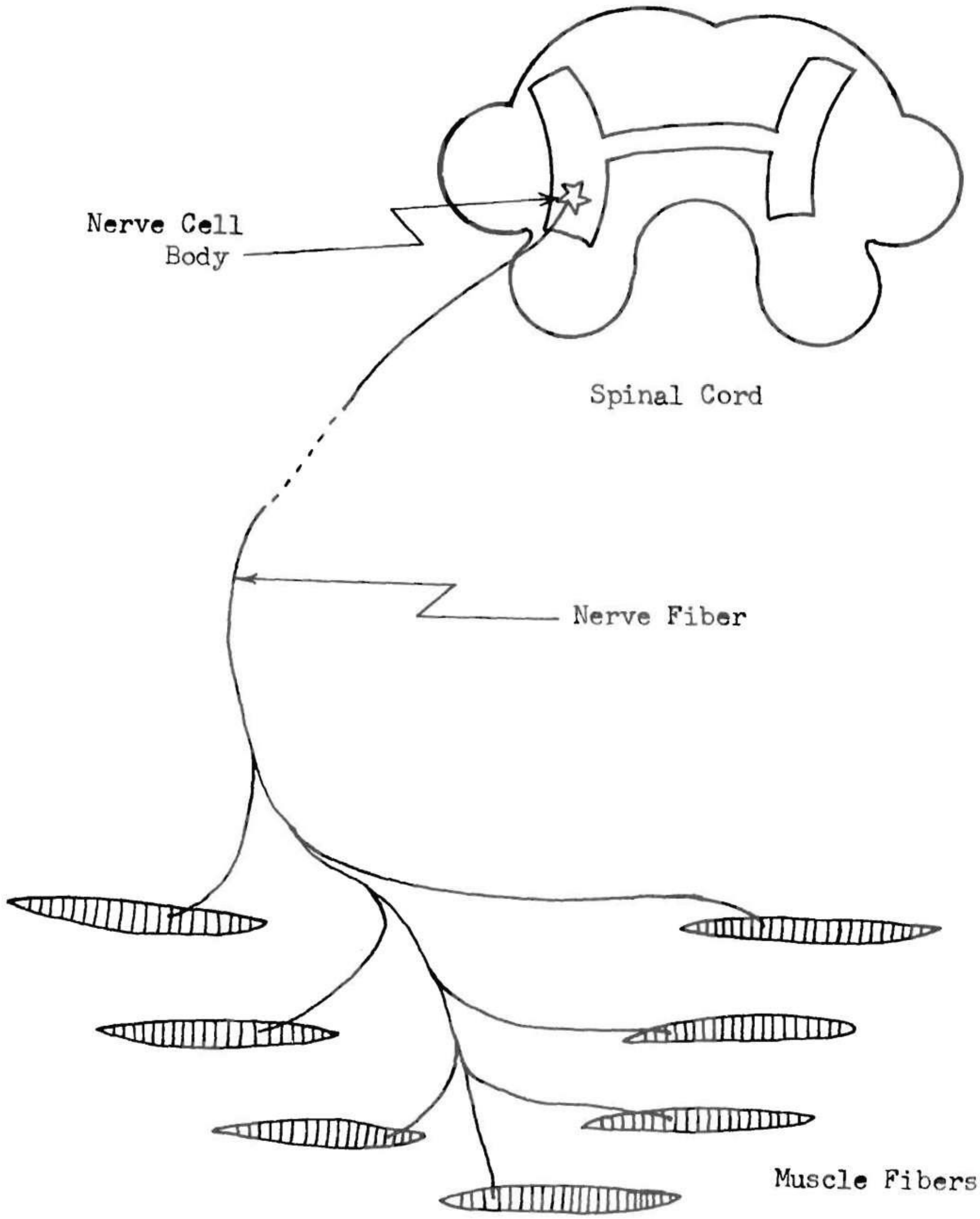


Figure 2. Scheme of a Motor Unit (From Basmajian)

is different, and the strength of a muscular contraction is controlled by the recruitment of more fibers as the nerve impulse becomes stronger.

If a muscle receives a single nerve impulse it contracts once or twitches. If, however, the muscle receives a series of nerve impulses in rapid succession, the twitches "add" and a single contraction is maintained. As was mentioned above, the motor units fire on an all or none basis, and the summated electrical activity of one motor unit is called the motor unit action potential. Since the motor units fire in all or none manner, there is a constant amplitude and duration of each motor unit potential (24). Thus, when a muscle is at rest there is a minimum of electrical activity associated with it. As minimal contractions are elicited, however, several motor units begin to fire. As the strength of the contraction increases the rate of firing increases, and at the same time, additional motor units are recruited.

<u>The Measurement of Muscle Tension</u>

The tension in a muscle is controlled by electrical activity or muscle action potential, and these action potentials can be detected and recorded by a technique called electromyography (EMG). According to Johnson (25), electromyography is the detection, amplification, indication, and recording of the electrical activity associated with muscle contraction.

Inman *et al*. (26) showed that the integrated electromyogram parallels the tension in a human muscle contracting isometrically, and in a study by Bigland *et al*. (27), it was shown that the electromyogram gives a measure of muscular tension in an isotonic contraction. Later, Wilcott and Beenken (28) showed that there is an essentially linear relationship between the force of muscle pull (isometric contraction) and the integrated electromyogram. Bergstrom (29) advanced the technique of electromyography significantly by showing that the relationship between the number of impulses and the integrated electromyogram is linear. According to Knowlton (30) the amplitude of the action potentials in the electromyogram is also a measure of muscle tension. Thus electromyography has emerged as a good method of measuring the force of muscular contraction for a muscle contracting isometrically.

The Anatomy of the Hand and Gripping

Skeleton

The bones of the hand are classified into three main groups, the carpals, metacarpals, and the phalanges of the fingers. The carpals are the wrist bones and they join the ulna and radius of the forearm. The metacarpals are the bones of the central part of the hand between the wrist and fingers, and the phalanges are the bones of the fingers (31).

Each finger consists of three phalanges and a corresponding metacarpal. The three phalanges in each finger are the proximal (first), the middle (second), and the distal (third) (32).

Muscles

The muscles of the hand can be classified into two groups, the intrinsic and extrinsic. The extrinsic muscles are of direct concern here since gripping strength is provided by members of this group. Specifically, flexion of the fingers (gripping) is done mainly by the flexor digitorum profundus and the flexor digitorum sublimis (33), which are located in the forearm. These muscles are connected to the fingers by long tendons, which are held in place at the wrist and palm of the hand by connective tissue, the flexor retinaculum (34). (Although the flexors digitorum profundus and digitorum sublimis provide the major portion of the gripping force, it should be kept in mind that other muscles take part in the gripping action as well, and there is some interaction between muscle groups.)

As was mentioned above, the movements of the hand can be classified as either prehensile or nonprehensile, and it is the prehensile (grip) with which we are concerned. Napier (35) further divides the prehensile grip into two subclassifications, the precision grip and the power grip. In the precision grip the object is pinched between the flexor aspects of the fingers and the opposing thumb, while in the power grip the object is held in a clamp formed by the partly flexed fingers and the palm. Counterpressure is supplied by the thumb.

There is continuity between the precision grip and the power grip and the position of the thumb indicates the amount of precision in the power grip. In general, the greater the force required of the grip the more the thumb is required to act as a "reinforcing mechanism," and the less it can contribute to precision. The limit is reached in the "coal hammer" grip of Napier, in which there is a minimum of precision and the thumb directly opposes the fingers.

CHAPTER III

INSTRUMENTATION AND EQUIPMENT

In order to investigate the effects of handle shape and diameter on muscle tension in holding, it was necessary to conduct an experiment in which a subject held handles of different shapes and diameters against a constant torque.

The Handles

There were 15 handles in all, each one 4 1/2 in. long and made of fir with a shaft 1 in. long for holding in a chuck. The handles were sanded and shelacked to provide a uniform surface finish.

Five diameters ranging from 11/16 in. to 1 7/16 in. in increments of 3/16 in. were arbitrarily selected to provide a range that was centered on Dreyfuss' optimum range (see page 2) and overlapped it equally at each end.

Three shapes were arbitrarily selected for the handles, a concave, cylindrical, and convex shape. The concave and convex handles were made so that their surface formed a circular arc of 9-in. radius. The diameter was defined to be the diameter at the center of the handle. Figure 3 shows the handle design.

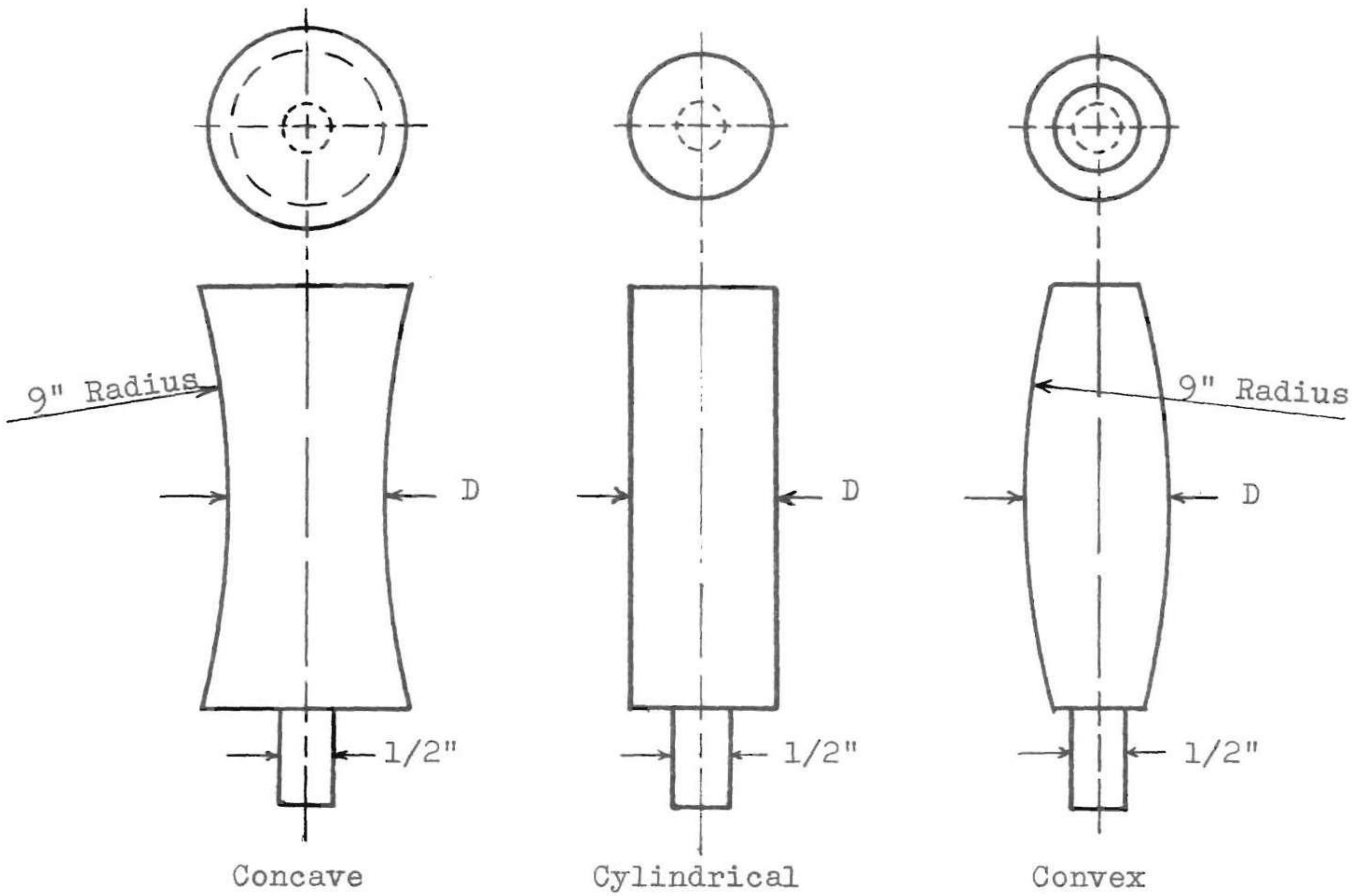


Figure 3. Handle Design

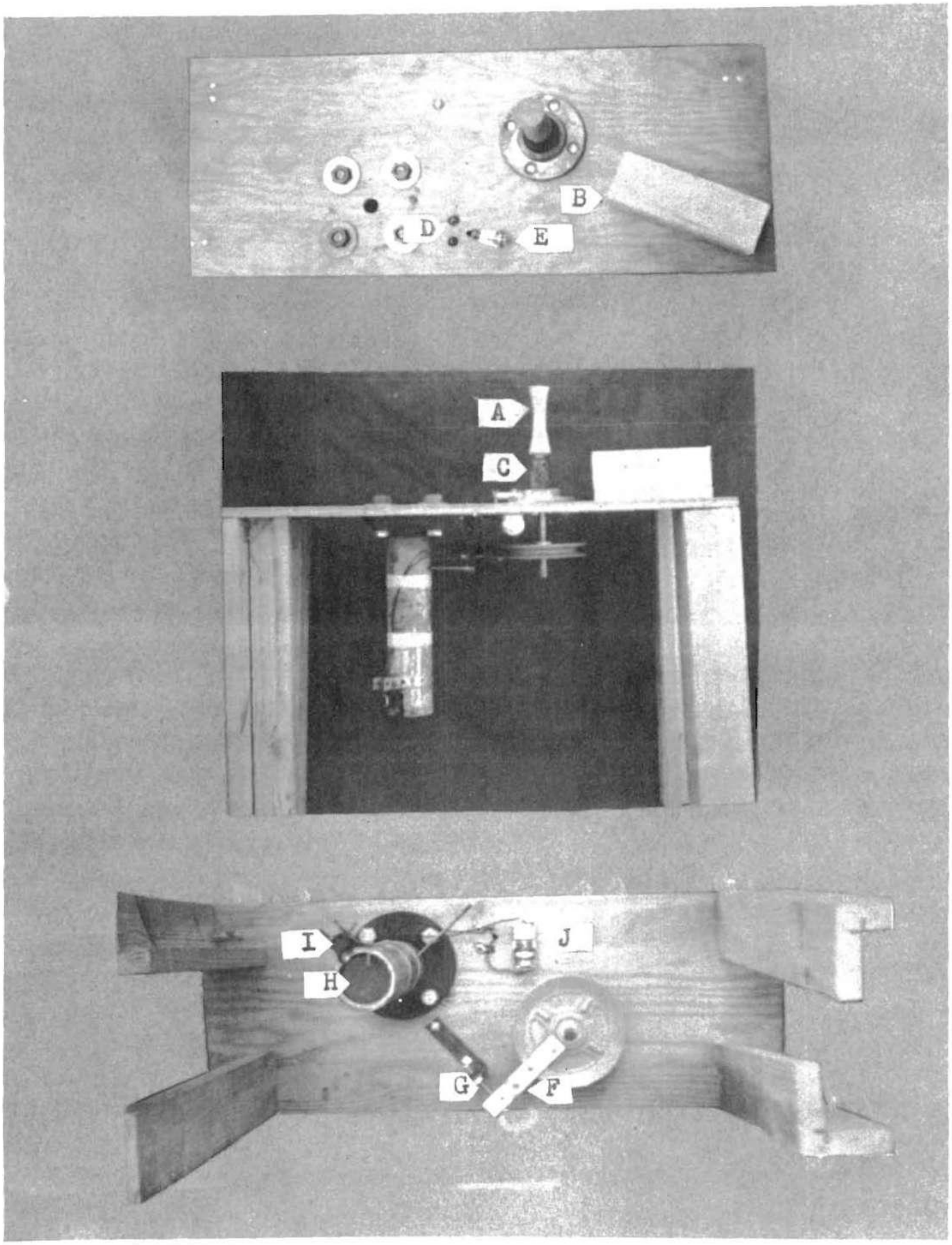
Special Apparatus

Special apparatus was constructed so that a constant torque could be applied to the handle while the subject held it, and at the same time, an electrical signal fed to the measuring equipment to indicate the beginning and end of the torque application.

This apparatus was built on a plywood table which was 12 in. wide, 31 in. long, and 22 in. high, upon which was mounted a floor flange. A chuck was placed in the flange which served as a bearing, and a 5/8 in. diameter shaft was passed through the table and bearing and the chuck secured to it with a set screw. A motor pulley was placed on the opposite end of the shaft below the table top. A 1-in.-wide flat steel bar 5 in. long was bolted to the pulley to serve as an arm.

One end of a piece of music wire was fastened to the arm 4 in. from the center of the shaft and the other end was passed over a 1-in. pulley and connected to a 4.4-pound (two kilogram) weight, so that a torque of 17.6 in.-pounds was applied to the handle. This torque value was arbitrarily selected so as to produce a muscular tension suitably larger than resting tension and yet not so large as to cause a too rapid onset of muscular impairment.

The weight was inside a 3-in. diameter pipe 1 foot long which was suspended from the bottom of the table. The pipe acted as a guide for the weight as well as a support



A.	Handle	D.	Signal Source	H.	Weight
B.	Arm Rest	E.	Lamp	I.	Switch
C.	Chuck	F.	Arm	J.	Battery
		G.	Stop		

Figure 4. Special Apparatus

for the 1-in. pulley, which was mounted inside it. A screw in the bottom of the pipe limited the gross downward movement of the weight and a screw stop on the arm provided fine adjustment of the position of the weight.

A 1 1/2 volt lamp was mounted on the top of the table where the subject could see it to indicate when the torque was applied to the handle. The lamp was turned on and off by a micro-switch, mounted at the bottom of the pipe, in contact with the weight so that when the weight was lifted the lamp would light.

Leads were connected in parallel with the lamp through banana jacks to provide a signal to the recording apparatus to indicate when the weight was raised and torque was applied to the handle. Electrical power for the lamp and signaling was provided by a 1 1/2 volt flashlight cell.

Measuring Apparatus

The measurement of the tension in the subject's forearm flexor muscle was done by electromyography. The apparatus was that of the Warm Springs Foundation, Warm Springs, Georgia, which was designed specifically for this purpose.

For this study surface electrodes were used to detect the subject's muscle action potentials. The voltages detected by these electrodes were fed into an amplifier made for the Foundation by Banker Electronics. The output from the amplifier was fed into a recording cathode ray oscilloscope. The oscilloscope was fitted with a 35 mm Fairchild oscillograph recording camera, for photographing the oscilloscope trace, and a periscope for monitoring the trace while it is being photographed.

CHAPTER IV

PROCEDURE

The handles and special apparatus described above were taken to the Warm Springs Foundation, Warm Springs, Georgia, and the experiment was conducted in their laboratory.

Subjects

Two subjects were used in the experiment. Subject number one was a male graduate student, 27 years old. He was right handed, five feet seven inches tall, and weighed 150 pounds, with a hand length of 7 3/8 in. Subject number two was a male undergraduate college student, 22 years old. He was right handed, five feet ten inches tall, and weighed 170 pounds, with a hand length of 7 1/2 inches. Both subjects passed a physical examination in January, 1963.

Preparation

Two trials of the experiment were made, one in the morning and the other in the afternoon. Subject number one was used in the morning trial and subject number two was used in the afternoon trial. In each trial the subject and special apparatus were placed in a grounded wire cage in order to minimize electrical interference with the measuring equipment.

Before the experiment was begun the subject was seated at the table and given written instructions for performing his task. After he had read the instructions the task was demonstrated to him and his questions about the procedure answered. The subjects were not told the object of the experiment, but both were able to guess it.

After the subject had received his instructions, surface electrodes were placed over his flexor digitorum sublimis muscle by the director of the Warm Springs Laboratory. For this study it was assumed that the tension measured in the flexor digitorum sublimis is proportional to the tension of the other finger flexing muscle groups. This assumption was necessary because of the practical difficulties in measuring the activity of the other muscles. The measurement of the action potentials of the flexor digitorum profundus, for example, requires the use of needle electrodes which are uncomfortable for the subject and difficult to place.

A commercial preparation known as EKG, a salt impregnated vanishing cream, was placed on the subject's skin at the points of electrode contact to reduce the electrical resistance of the junction. The positive electrodes were placed over the flexor sublimis muscle and held there by surgical tape. The ground electrode was placed on the upper arm and held in place by an elastic band. This location for the ground electrode was used instead of the wrist, as is normally used, to reduce electrical interference with the measuring equipment.

The Experiment

The subject sat at the table with his arm on a wooden rest and his hand positioned ready to grasp the handle which was secured in the chuck.

The subject was instructed to relax while the tension in his flexor muscle was monitored on the oscilloscope by the director of the laboratory. When the muscle tension reached the resting level the experimenter was notified and the signal "on" was given. At this time the subject grasped the handle in a power grip and turned it clockwise until the lamp on the table top came on. This turn was made through an angle of approximately five degrees, so that the weight was raised away from the stops and the 17.6-in.-pound torque was applied to the handle.

When the lamp was lighted the subject held the handle stationary against the constant torque while the action potential of his flexor muscle was recorded on film (see below), for later analysis. Upon the signal "off" the subject released his grip.

Each handle was tested with each subject once, and it was assumed that there was no interaction between the subject and the shape or diameter of the handle. The duration of the test on each handle was approximately five seconds, so that a two-second holding period could be measured after the handle was turned and before it was released, in case the subject made an assistive release.

It was assumed that by having the subject turn the handle and apply the torque himself that the feedback from his feel of the grip would cause him to apply a natural grip pressure to the handle.

There was a rest pause of at least two minutes between tests on each handle so that the subject's muscle could recover from the contraction. For difficult grips the rest period was extended to five minutes.

The handles were numbered and presented to the subject in a predetermined random order to reduce muscle training and learning effects. A different order was used for each subject.

Data Collection

The muscle action potentials detected by the electrodes were amplified with suitable values of gain and fed into the oscilloscope. The gain on the oscilloscope time axis was reduced to zero, so that the output was a horizontal line whose length was proportional to the action potential being measured. The camera was started and the film passed in front of this line at a constant speed. Thus a graph of action potential versus time was obtained. The time scale was marked on the film by an electronic time marker in one-second intervals. The time during which the torque was applied to the handle was indicated by an electrically produced change in the position of a line parallel with the time axis.

CHAPTER V

RESULTS

Raw Data

Since the measurements of muscle action potential were in the form of an oscillograph on 35 mm film, it was necessary to extract the data from the graph by measuring the width of the trace. This width was proportional to the action potential, and was compared with calibration traces which were placed on the film electrically. These calibration traces corresponded with the amplifier gain setting used in making the measurements.

The raw data were extracted from the film record by first projecting the calibration trace onto graph paper with a film strip projector and adjusting the projection to a suitable scale, and then projecting the test trace and measuring its width relative to the calibration scale. The data were then adjusted by subtracting the base line width from each measurement.

The resulting data were a measure of twice the absolute action potential, but since this study is concerned with the relative values of the action potentials the data were used in this form for convenience. If one wishes to find the absolute value of the muscle action potentials, it is necessary to multiply the value by one half. Table 1 shows the adjusted tension data for each subject and handle.

Analysis

The measurements were analyzed with the analysis of variance technique. This technique uses the model

$$X_{ij} = M + R_i + C_j + I_{ij} + E_{ij}$$

where:

X_{ij} is the outcome of the experiment using the ith row and jth column.

M is a general mean.

R_i is the effect of the ith row.

C_j is the effect of the jth column.

I_{ij} is the interaction between the ith row effect and the jth column effect.

E_{ij} is a random effect.

In this study the subjects' effect (row) was treated as being random, since the subjects were selected from a large population of possible subjects. Thus R_i is a random variable with mean zero and variance S_R^2.

The effects of the shapes and diameters of the handles were treated as being fixed, since the study was concerned only with differences between the handle shapes and diameters tested. Thus C_j is the deviation from the average effect of shape or diameter.

Table 1. Muscle Tension for Handles by Subjects

Handle Number	Shape	Diameter	Muscle Tension* Subject No. 1	Subject No. 2
1	Concave	11/16"	165	118
2	Concave	7/8"	100	158
3	Concave	1 1/16"	140	98
4	Concave	1 1/4"	105	78
5	Concave	1 7/16"	95	83
6	Cylindrical	11/16"	285	458
7	Cylindrical	7/8"	190	208
8	Cylindrical	1 1/16"	145	148
9	Cylindrical	1 1/4"	65	98
10	Cylindrical	1 7/16"	75	93
11	Convex	11/16"	1050	890**
12	Convex	7/8"	145	168
13	Convex	1 1/16"	125	93
14	Convex	1 1/4"	125	113
15	Convex	1 7/16"	190	123

* Measured in microvolts of action potential

** This value represents maximum measured effort in unsuccessful attempt to perform task.

It was assumed that there was no interaction between the subjects' effect and the handle shape effect. Consequently the interaction term I_{ij} is reduced to zero.

The subject effect and shape effect were considered to be crossed in that all levels of the one effect were combined with all levels of the other effect (36). The diameter effect was considered to be nested within shape because of the arbitrary definition of diameter. Under this definition, diameter was a characteristic of the particular shape to which it belonged. Thus, while there may be variations among diameters, it would be within each shape (37).

Since it was assumed that there was no interaction between subjects and handle shape or between subjects and diameter, the interaction terms subject x diameter and subject x shape were combined to form the residual, or error term. The shape effect and diameter effect were both tested against this error term and both were found to be significant at the 1 per cent level of significance. In other words, there was a chance of 1 per cent or less of falsely concluding that there were real differences in shapes and diameters, when in reality the apparent differences were the result of chance causes.

Since there were significant differences between shapes and between diameters, a multiple range test (38) was made to determine the rank between the mean muscle tensions for shapes and diameters within shapes. This test showed that, at the 5 per cent level of significance, the mean muscle tension for the convex shape was largest. The cylindrical shape produced the second highest mean tension and the concave shape produced the least mean tension.

A multiple range test on diameters within shapes showed no significant differences between the diameters of the concave shape at the 5 per cent level of significance. The test did show significant differences between the diameters of the other two shapes, however.

The smallest diameter (11/16 in.) of the cylindrical shaped handles produced a higher mean tension than the other handles in this group at the 5 per cent level of significance. The test showed no significant difference in the mean tension values for the 7/8 in. and 1 1/16 in. diameter cylindrical handles, but the mean for these two diameters was significantly lower than that of the 11/16 in. diameter. The test also showed no real difference in the mean tensions of the 1 1/4 in. and 1 7/16 in. diameter cylindrical handles, although the tensions for these diameters were significantly lower than the others in the cylindrical group.

The diameters of the convex shaped handles were also tested at the 5 per cent level of significance, and no significant difference in the mean tension values of the four larger diameters was found. The mean tension of the 11/16 in. convex handle was found to be significantly higher than that of the other four at the 5 per cent level of significance.

Figures 5 and 6 show the results of these multiple range tests.

Upon examining the results of the foregoing analysis it was noticed that the magnitudes of the muscle tension values for the 11/16 in. diameter in the cylindrical and convex shapes were considerably disproportionate to those of the other diameters in these shapes. It was suspected that at the 11/16 in. level of diameter the relationships between shapes and diameters were different from those of the four larger sizes. For this reason a second analysis was made with the values for the 11/16 in. diameters excluded, in order to determine whether the differences in shapes were actually consistent throughout the range of diameters or were peculiar to the 11/16 in. diameter.

The second analysis showed no significant differences between shapes at the 5 per cent level of significance when only the four larger diameters are considered. The analysis did show that there were significant differences in the four larger diameters at the 5 per cent level of significance.

A multiple range test was made, at the 5 per cent level of significance, in order to determine the relative ranking between the mean tension values for the four larger diameters. The test showed no significant difference between the mean muscle tensions for diameters of the concave

Shape	Concave	Cylindrical	Convex
Mean Muscle Tension	114.0	176.5	302.2
Nonsignificant Groupings (Five per cent level)	———	———	———

Figure 5. Results of Multiple Range Test on Shapes for all Diameters

Shape	Concave				
Diameter	11/16"	7/8"	1 1/16"	1 1/4"	1 7/16"
Mean Tension	141.5	129.0	119.0	91.5	89.0
Nonsignificant Groupings (Five per cent level)	———	———	———	———	———

Shape	Cylindrical				
Diameter	11/16"	7/8"	1 1/16"	1 1/4"	1 7/16"
Mean Tension	371.5	199.0	146.5	81.5	84.0
Nonsignificant Groupings (Five per cent level)	———	———	———	———	———

Shape	Convex				
Diameter	11/16"	7/8"	1 1/16"	1 1/4"	1 7/16"
Mean Tension	970.0	156.5	109.0	119.0	156.5
Nonsignificant Groupings (Five per cent level)	———	———	———	———	———

Figure 6. Results of Multiple Range Test on all Diameters

and convex shapes, but it did show that there were significant differences in the mean muscle tensions for diameters within the cylindrical shape.

For the cylindrical shape the test showed no significant difference between the mean muscle tensions of the 7/8 in. and 1 1/16 in. diameters and no difference between the mean muscle tensions of the 1 1/4 in. and 1 7/16 in. diameters. There was, however, a significant difference between the mean muscle tensions of these two pairs of diameters in that the 1 1/4 in. and 1 7/16 in. diameter pair shows a significantly smaller mean tension than the 7/8 in. and 1 1/16 in. pair.

Figure 7 shows the results of the second multiple range test on the four larger diameters.

The next step in the analysis was the calculation of the contribution of the variance of each effect toward the total variance. The variance of the individual effects were estimated using their respective mean squares, and the calculation of the contribution of each effect variance toward total variance was made for the case in which the 11/16 in. diameter values were used (first analysis) as well as the case in which the 11/16 in. diameter values were excluded (second analysis).

In the first case, where the analysis was made using the 11/16 in. diameter, the variance due to the shape effect accounted for 14.5 per cent of the total variance

Shape	Concave			
Diameter	7/8"	1 1/16"	1 1/4"	1 7/16"
Mean Tension	129.0	119.0	91.5	89.0
Nonsignificant Groupings (Five per cent level)				

Shape	Cylindrical			
Diameter	7/8"	1 1/16"	1 1/4"	1 7/16"
Mean Tension	199.0	146.5	81.5	84.0
Nonsignificant Groupings (Five per cent level)				

Shape	Convex			
Diameter	7/8"	1 1/16"	1 1/4"	1 7/16"
Mean Tension	156.5	109.0	119.0	156.5
Nonsignificant Groupings (Five per cent level)				

Figure 7. Results of Multiple Range Test on Four Larger Diameters

and the variance due to the diameter effect accounted for 81.1 per cent of the total variance.

In the second case, in which the values for the 11/16 in. diameter were excluded, the shape effect contributed 7.1 per cent of the total variance compared with 56.7 per cent of the total for the diameter effect.

It is important to notice that the variance due to diameter is in both instances a greater part of the total variance than is the shape variance, even though the shape effect was found to be significant in the first case where the 11/16 in. diameter values were used but not in the second case in which the 11/16 in. diameters were excluded.

CHAPTER VI

LIMITATIONS AND CONCLUSIONS

Limitations

Several limitations were imposed on the experimental arrangement, and these limitations should be recognized so they can be considered in the evaluation of the conclusions drawn from this study.

In the first place, the number of observations was small, and there was only one replicate per subject-handle combination. These conditions severely limit the discovery and treatment of possible interactions between handles and subjects, as well as limiting the sensitivity of the techniques employed in the analysis of the data.

In the second place, owing to time and equipment availability restrictions, the number of subjects used in the experiment was small. Furthermore, the subjects were selected from one age group and the selection was done on the basis of their physical condition and willingness to leave their personal business to travel out of town. Thus subject selection cannot be considered random in the strict sense of the word.

It should be noted that there are many different handle shapes, of which three were arbitrarily selected for study, and there are many possible choices of diameter, of which five were used.

It should also be recognized that certain assumptions were made concerning the relationship of tension in the muscle tested and other muscles in the finger flexing group, and the subject's application of grip pressure in holding the handle. Since these assumptions are not considered severe, they are not verified.

Conclusions

Upon examining the results of this study the following conclusions were reached, subject to the limitations of the study:

(1) Using tension in the finger flexing muscles as the criterion for comparison of the handle shapes tested, there is no real difference between the shapes in the diameter range of 7/8 in. to 1 7/16 in.

(2) There are differences between the shapes tested in the 11/16 in. diameter, such that in this diameter the convex shape is inferior and the concave shape is superior to the cylindrical shape.

(3) Handle diameter has a greater influence upon muscle tension in gripping the handle than does handle shape for the shapes and diameters tested.

(4) Dreyfuss' recommendation of 7/8 in. as the lower limit for handle diameter is substantiated

with respect to finger flexing muscle tension for the cylindrical and convex shaped handles tested.

(5) For the three shapes tested the larger handles, 1 1/4 in. and 1 7/16 in. diameter, are superior in the cylindrical shape but do not make a significant difference with the other shapes.

CHAPTER VII

RECOMMENDATIONS

It is recommended that in future studies of the effect of handle diameter and shape on muscle tension a larger number of subjects be used and several replications made for each subject on each handle. In this way it may be possible to detect smaller differences between shapes and diameters at higher levels of significance. In future studies of this nature a greater range of diameters should be used.

In this study the definition and selection of shapes were arbitrary, and it may be possible for future researchers in this area to devise a means of quantifying shape along a continuum. It may be that this quantification could be done by taking the definition of shape to be the curvature of the handle surface. (Curvature is defined to be the reciprocal of the radius of curvature.) If this were done it may be that shape could be treated as a continuous quantity in that convex shapes would become shapes with positive curvature, cylindrical shapes would become shapes with zero curvature, and concave shapes would be redefined to be shapes with some sort of "negative" curvature. Such a treatment would facilitate an investigation of the shape-diameter response surface.

It may be worthwhile to investigate the effects of handle material and length on muscle tension, as well as the different methods of gripping and position of the handle.

It is also recommended that a study be undertaken to investigate the roles and interactions of muscle groups other than the forearm flexor group in gripping.

APPENDIX

Table 2. Raw Data for Subject Number One

Handle Number	Gain Setting	Calibration Trace	Trace Width (Microvolts)	Base Line (Microvolts)	Adjusted M.A.P.
1	1-2	100 uv	180	15	165
2	1-2	100 uv	115	15	100
3	1-2	100 uv	155	15	140
4	1-2	100 uv	120	15	105
5	1-2	100 uv	110	15	95
6	1-2	100 uv	300	15	285
7	1-2	100 uv	205	15	190
8	1-2	100 uv	160	15	145
9	1-1	100 uv	80	15	65
10	1-1	100 uv	90	15	75
11	10-3	1 mv	1100	50	1050
12	1-2	100 uv	160	15	145
13	1-2	100 uv	140	15	125
14	1-2	100 uv	140	15	125
15	1-2	100 uv	205	15	190

Table 3. Raw Data for Subject Number Two

Handle Number	Gain Setting	Calibration Trace	Trace Width (Microvolts)	Base Line (Microvolts)	Adjusted M.A.P.
1	1-2	100 uv	120	2	118
2	1-2	100 uv	160	2	158
3	1-2	100 uv	100	2	98
4	1-2	100 uv	80	2	78
5	1-2	100 uv	85	2	83
6	1-1	100 uv	460	2	458
7	1-2	100 uv	210	2	208
8	1-2	100 uv	150	2	148
9	1-2	100 uv	100	2	98
10	1-2	100 uv	95	2	93
11	10-3	1 mv	900	10	890*
12	1-2	100 uv	170	2	168
13	1-2	100 uv	95	2	93
14	1-2	100 uv	115	2	113
15	1-2	100 uv	125	2	123

*This value represents maximum measured effort in unsuccessful attempt to perform task.

Table 4. Random Order of Handle Presentation

Trial Number	Handle Number, Subject One	Handle Number, Subject Two
1	4	2
2	11	9
3	10	1
4	9	14
5	13	5
6	8	8
7	14	10
8	2	11
9	5	13
10	3	3
11	1	4
12	7	7
13	6	15
14	12	6
15	15	12

Instructions for Subjects

Thank you for your help in this study. Please be seated at the table and roll up your right sleeve.

Electrodes will be placed on your forearm and held in place with tape. These electrodes pick up the very small voltages generated within your body which will be recorded in the experiment, much like an electrocardiogram. The electrodes do not carry current to you, and you will feel no electric "shock."

Before you is a chuck in which handles will be placed. You are requested to hold the handle like you would a screwdriver, and on signal to light the small bulb in front of you and hold it on by turning the handle clockwise ("tightening"). The signal for lighting the bulb and keeping it lit will be the word "ON." When you hear the word "OFF" let the handle return to its original position, take your hand away, and relax. You may adjust the arm rest as you wish so long as it does not interfere with the electrodes or other equipment. (The experimenter will demonstrate the procedure.)

If you need to go to the rest room or drink water, do so now because once the experiment has begun you will not have an opportunity until it is over.

If there is anything about the procedure which you feel has not been adequately covered, please ask about it now. However, questions pertaining to the object of the experiment or the measurements being made should be held until after the experiment is run. At that time the details will be explained to you if you wish.

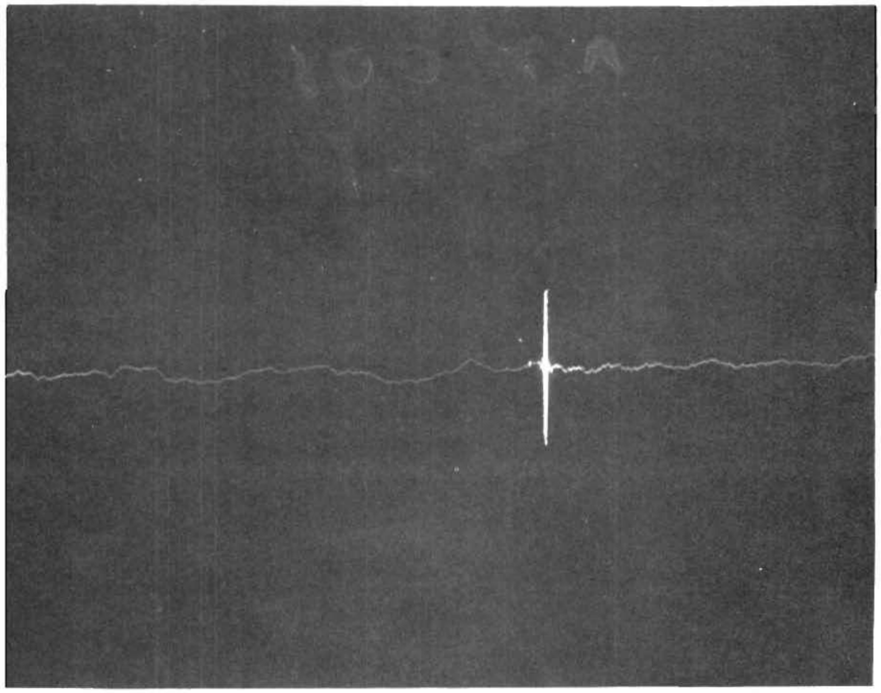
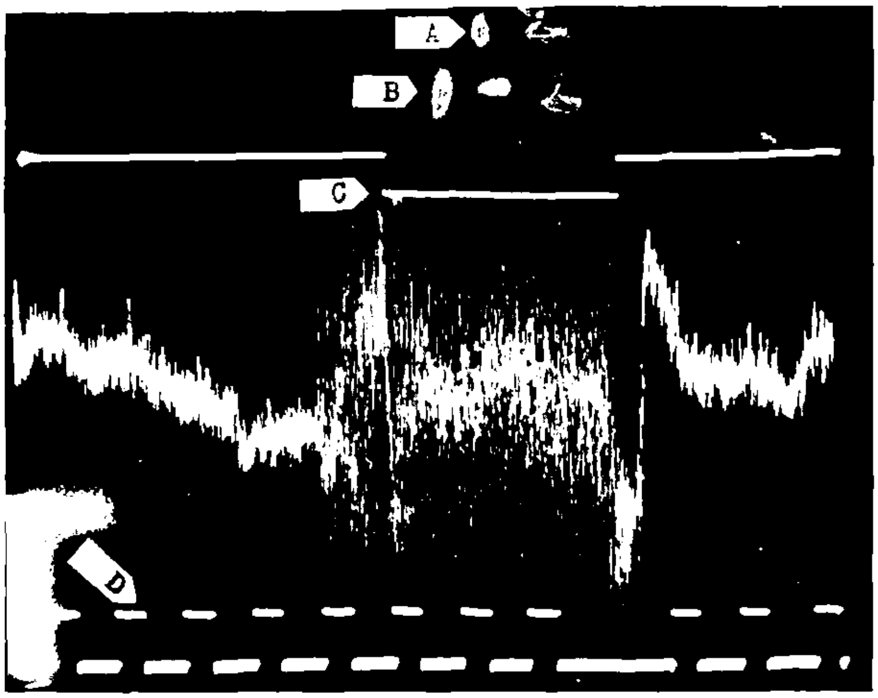


Figure 8. Sample Calibration Trace



A. Handle Number

B. Gain Setting

C. Torque Application

D. Time Mark

Figure 9. Sample Muscle Action Potential Trace

Table 5. Summary of Analysis of Variance with 11/16" Diameter Included in the Analysis

Source of Variation	Sum of Squares	Degrees of Freedom	Mean Square	F Ratio
Shape	183,753.27	2	91,876.60	36.07
Diameter	1,236,904.60	12	102,919.38	40.41
Subjects	177.64	1	177.64	
Error Term	35,657.86	14	2,546.99	

Table 6. Summary of Analysis of Variance with 11/16" Diameter Excluded from the Analysis

Source of Variation	Sum of Squares	Degrees of Freedom	Mean Square	F Ratio
Shape	3,393.75	2	1,696.88	2.70
Diameter	25,059.37	9	2,784.37	4.44
Subjects	63.37	1	63.37	
Error Term	6,903.13	11	627.56	

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